

**Considerations on spatial crop load mapping**

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### Abstract

Crop load, the ratio of vine size to mass of fruit harvested, is a fundamental principle in understanding viticulture. Measuring vine size and crop yield, the components of crop load, has historically been a labour intensive exercise that has limited the use of crop load information as a management tool in commercial vineyards. Recent advances in assessing vine vigour, size and yield using geo-referenced sensors is starting to make high resolution crop load mapping a reality for the industry. In this paper, the concept of crop load is revisited with an emphasis on how vine size and yield can be mapped in vineyards. The existing literature is reviewed on how vine size and yield vary spatially and temporally within vineyard blocks and the inference this has on the spatio-temporal variability of crop load. An example of crop load mapping using sensor technology is presented to illustrate recent advances in sensor technology in viticulture. Finally, some emerging technology and knowledge gaps for implementing spatial crop load information into vineyard management are discussed.

### Keywords

canopy sensing, spatial variability, vine balance, vine size, yield

### Introduction

Grape production is achieved by balancing interactions between the environment (e.g. site selection, season length, growing degree days, etc.), genetics (e.g. variety selection or breeding improvement) and management (e.g. training systems, pruning strategies and irrigation) at a site (Howell 2001). Of these, the meso- and macro-climatic and genetic components in commercial systems are relatively stable in the short- to medium-term (Coombe and Dry 2005), and are difficult for growers to manipulate. In contrast, vineyard management can be altered quickly to affect the micro-climate and the amount of leaf area and/or fruit of a vine, and this is known to have a potentially large effect on productivity – both quantity

and quality (Shaulis et al. 1966, Smart and Robinson 1991, Coombe and Dry 2006). Adapting and improving vineyard management is therefore key to altering productivity in the short term (within 1-10 years).

The relationship between the vegetative and reproductive growth of a vine influences its productivity and fruit quality (Howell 2001, Kliewer and Dokoozlian 2005, Petrie and Clingeleffer 2006). Perennial vine health and consistent achievement of production goals hinge upon balancing this relationship. This concept of ‘balance’ underpins all crop production. To optimize production, a plant’s demand for photosynthate (its ‘sinks’) should equal its ability to generate photosynthate (its ‘sources’). Undercropping or overcropping affects the development and maturity of the reproductive and storage organs (typically the harvestable parts of plants), and affects production. Manipulating this ‘balance’ in vineyards (via fruit thinning and/or leaf thinning) can effect on profitability across all cultivars, growing regions and markets (wine, juice, table and raisin).

In viticulture, the term ‘*vine balance*’ is used colloquially in the context of how the sinks and sources relate to each other. However, it is not possible to quantify all the sinks or all the sources in a vine. For example, the below ground biomass of a vine cannot be measured non-destructively but is an important sink. In the scientific literature, the quantitative term ‘*crop load*’<sup>1</sup> is preferred to vine balance. Crop load is quantitative as it is defined using measurements of accessible vine tissues that relate to the production of or demand for photosynthate. Specifically, crop load is expressed either as fruit load (yield) per dormant pruning mass (Ravaz 1911, Partridge 1925), or as leaf area per fruit mass (Shaulis et al. 1966, Kliewer and Dokoozlian 2005). In calculating crop load, only the harvested sinks are measured, while the

<sup>1</sup> Crop Load should not be confused with the terms crop size, fruit load and crop level that are also used in the literature and respectively are only concerned with the reproductive growth of a vine, the total yield of fruit harvested per vine and the total yield per unit land area, and do not pertain to the vegetative growth of a vine. Similarly, vine capacity is a common term also but is used to describe the sum of reproductive and vegetative biomass produced in a growing season (Dokoozlian and Kliewer 1995) and is not indicative of the balance between the two.

functional leaf area is only estimated from pruning mass (PM) or a non-destructive observation of leaf area.

The target crop load within a system only applies to that system (or similar systems). Furthermore, even within a system, the optimum crop load at a site will depend on production objectives and local environmental factors. Therefore, while optimum crop load values have been cited between a range of five and ten for the Ravaz Index and 11 to 14 cm<sup>2</sup> leaf area per g fruit, (Bravdo et al. 1985, Naor et al. 2002, Kliewer and Dokoozlian 2005), a simple prescription approach to crop load (or vine balance) management will not promote viticultural and economic sustainability (Howell 2001). Crop load metrics are extremely useful in understanding if production is 'balanced' or not but are always specific to the production system being studied.

Managing crop load to ensure fruit reaches maturity, a threshold that varies according to production system, is especially important in regions where the growing season is limited by thermal time, such as the Lake Erie Region in NY, USA (Bates 2006 and 2008). In the juicegrape market, premiums are paid based Juice Soluble Solids (JSS, °Brix). Data from this system (Figure 1, *Vitis labruscana* cv. Bailey) indicates that a leaf area to fruit mass ratio of 15 cm<sup>2</sup> g<sup>-1</sup> is economically optimum for maximising yield while ensuring the minimum quality standard (17 °Brix) is met (Dr Terence Bates, Cornell Lake Erie Research and Extension Laboratory, Cornell University, *pers. comm.*). In this example, overcropping (<15 cm<sup>2</sup> g<sup>-1</sup> in Fig. 1) corresponds to a reduction in °Brix at harvest and could result in failure to meet the minimum quality standard in severe cases (<10 cm<sup>2</sup> g<sup>-1</sup>). Secondary consequences include reduced cold hardiness, stalled root growth and diminished yield potential in the following season due to a combination of inhibited shoot growth and bud fruitfulness (Winkler 1954, Winkler et al. 1974). Undercropping (>15 cm<sup>2</sup> g<sup>-1</sup> in Fig. 1) reduces production tonnage without a proportional increase in ° Brix, so is economically inefficient. The benefits of balancing crop load and the consequences for imbalance illustrated in this example extend across production systems regardless of how fruit quality is delimited (Bravdo et al. 1985, Kliewer and Dokoozlian 2005). However, in situations where the ripening period can be

consistently extended (Keller et al. 2004, McDonnell et al. 2008), where JSS accumulation is primarily limited by water deficit (Santesteban et al. 2010) or where super-premiums are paid to offset perennial reduction in yield, balancing crop load may not provide equivalent benefit to cost.

<<FIGURE 1 HERE>>

Figure 1. The influence of crop load, expressed as a leaf area to fruit mass ratio, on total soluble solids (°Brix) at harvest in Concord (*Vitis labruscana* cv. Bailey) vines in the Lake Erie viticulture region (Latitude 42.4°N). Leaf area was measured at maximum canopy fill and fruit mass and °Brix were measured at harvest. Optimum level of total soluble solids at harvest (17 °Brix) was reached when leaf area is balanced with fruit mass at a ratio of 15 cm<sup>2</sup> g<sup>-1</sup>. Lower values lead to immature fruit while higher values could have ripened more fruit without any effect on quality (°Brix) premiums.

In 2001, Howell hypothesised that effective crop load management will result from the ability to precisely measure and manage vineyard variation using sensors linked to Global Navigation Satellite Systems (GNSS). Howell’s observation was made at the start of the development of Precision Viticulture (PV). PV is the application of general Precision Agriculture (PA) methodologies and technologies to manage viticultural systems at finer spatial and temporal scales (Bramley and Proffitt 1999). For crops, site-specific management means moving away from average field or vineyard management and toward identifying production potential at sub-field scales, where input is precisely applied at a specific time and place (Bongiovanni and Lowenberg-Deboer 2004, Whelan and McBratney 2000). The generation of spatial information on vine size and yield in viticulture has been enabled by the emergence of canopy and yield sensors in the mid to late 1990s (Tisseyre et al. 2007, Arnó et al. 2009). These have taken some time to mature into commercial products and have still not been perfected (Matese et al. 2015, Taylor et al. 2017).

PA for annual row crops (maize, wheat, soybean, etc...) is heavily focused on soil resource management, especially nutrient management. The production system is reset each year and growers have annual opportunities to improve productivity by changing genetics (new varieties) or the agronomic system. PA is different for perennial fruit crop production systems, including vineyards, as there are longer-term interactions between the soil, vine and management at each site that need to be optimised for environmental, viticultural and economic outcomes. In particular, the vegetative and reproductive growth in any given year can impact production in the following year. In perennial systems, the economic optimisation is usually more strongly associated with both product quality and quantity than in broad acre annual systems.

Existing soil and crop sensors have been adopted and adapted from row crops into vineyard systems and there have been new viticulture-specific sensors developed. However, the methodologies to process, integrate and derive decisions from the data are still required and must be tailored for viticulture. One application that would optimize vineyard production goals is to use sensor technologies to spatially characterise variation in both crop and canopy, and therefore crop load, throughout vineyards. Currently, however, most grape growers do not objectively measure spatial variation in either vine size or yield. When data are collected, site-specific management tends to be applied for either canopy or yield management, but not the interaction of the two, even though the interaction has recently been shown to improve management options (Urretavizcaya et al. 2017). Therefore, despite developments in PV over the past 20 years, there is a current knowledge gap in understanding the variability in crop load in vineyards and the potential importance that its spatial management has for productivity across a wide range of viticultural systems. To address this knowledge gap and promote development in spatial Crop Load vineyard management, this paper will (1) briefly review how crop load has traditionally been (aspatially) estimated and measured, (2) review new and emerging methods for spatially measuring and interpreting vine size and yield components, (3) synthesise existing information on the spatial and temporal variability of vine size and yield components within vineyards, (4) briefly evaluate how these components interact

spatially and temporally to influence spatio-temporal variance in crop load, (5) discuss mapping crop load in vineyards and (6) propose advances to facilitate the adoption of spatial crop load management in vineyards.

**Traditional means of estimating and measuring vine size and yield (primarily in research, as opposed to commercial, settings).**

*Vine Yield/Fruit Load:* Vine yield, or fruit load, is the mass of grapes produced by a vine. It is determined by the number of clusters set (a function of shoot number and fruitfulness), the (average) number of berries in a cluster, and the average berry mass. (Clingeleffer et al. 2001). Since grapes are the harvested commodity, yield assessment is a routine operation in commercial vineyards but is generally restricted to a gross harvest mass per vineyard, or to manual in-season yield estimations. Thus, vineyard or block-level information on the *mean* yield is generally well recorded in the industry, although yield *variance* at any scale (block or vineyards) is not typically recorded.

Weighing crop yield at commercial harvest is the only way to audit production. Harvest yield monitoring is done in several ways. For (high-value) hand-harvested systems, a field scale and picking bins are used to weigh the crop but this requires detailed logistics and incurs a large cost. In mechanically harvested systems, weights are obtained on delivery to the crush or winery thereby providing block or vineyard level yield data. However, it is difficult to assign bin/gondola weights to specific locations in the vineyard to identify sub-vineyard scales of yield variation.

In-season yield estimation involves manual counts of either one or multiple yield factors. These are usually cluster number and berries/cluster as they are temporally stable after fruit set (Dunn 2010). Berry mass can also be estimated from historical records (Dami 2006). The efficacy of mid-season yield estimation is very dependent on the sampling scheme used and the rigour of data collection. An error in any one factor has a multiplicative effect on final crop estimation when assessing multiple factors. Yield estimation generates information on both the mean and the variance in forecasted yield; this is not to say

that it is always done well. For example, the absolute difference between in-season estimated and actual at-harvest mean yield of different vineyard blocks has been measured at 30% (Dunn 2010). There is a need for improved methods to estimate vineyard crop yield so that over and undercropped situations can be precisely managed proactively rather than retroactively.

*Vine/Canopy size:* Vine and canopy size are both used in reference to the source size for crop load. Typically, pruning mass (PM) is used for vine size, e.g. in the Ravaz Index, and canopy size is used when Crop Load metrics use leaf area index (LAI). For simplicity, the term “vine size” will be synonymous with both PM and LAI throughout this document.

To obtain measurements in research situations, manually stripped leaves are run through a leaf area meter to directly measure LAI, however destructive measures are not desirable in commercial situations. The most common method for estimating vine size has been the pruned mass of one-year old canes during the dormancy period (Ravaz 1911, Partridge 1925, Shaulis and Steel 1969). Measuring PM has several advantages: it is easily repeatable, requires little training, is appended to a necessary vineyard practice (pruning) and is not overly sensitive to the timing of measurement once the wood is dormant and moisture content stable. The drawback is that PM provides information on vine size post-harvest, precluding potential proactive in-season management.

To achieve more timely information, non-destructive, within-season, canopy-based vine size estimators have also been developed and evaluated. These include;

- i) estimations of the exposed leaf area based on average external geometric canopy shape and point quadrat analysis (PQA) (Smart and Robinson 1991) that can be enhanced with ceptometry (Meyers and Vanden Heuvel 2008).
- ii) Shoot counts, shoot length measurements and individual mid-rib leaf lengths to estimate total vine leaf area on individual vines (Bates 2008), which in turn can be translated to estimates of pruning mass (PM).



- iii) Various LAI measurement sensors (e.g. LAI-2200C Plant Canopy Analyzer; Li-Cor, Lincoln, NE).
- iv) Point grid and fisheye photography to quantify total light interception to estimate dry matter production (Wünsche et al. 1995).

Trunk circumference (or diameter) (TC) at a fixed height above the ground is an alternative potential indicator of vine size. TC correlates with PM in some vineyards (King et al. 2014; Trought et al. 2008) and is probably most useful in non-irrigated vineyards in water-limiting environments, where trunk circumference is integrative of local vine vigour over time (Tisseyre et al. 2007, Santesteban et al. 2010, Acevedo-Opazo et al. 2011). TC measurements are straightforward, quick and can be done year-round (i.e. has no time restriction on acquisition). TC is a relative measurement and does requires local calibration to a direct measurement of vine size, such as PM. It has some limitations, such as in areas where winter damage can deform or kill vines resulting in trunk renewal practices and variable trunk ages in a vineyard.

All traditional approaches are labour-intensive point-in-time measurements and, while they give good site-specific estimations of vine size, the time required to generate high-resolution data for vine size mapping is only realistic in a research context. Commercial applications for crop load mapping are therefore limited. Traditional canopy and PM measurements do, however, play a role in calibrating and ground-truthing indirect high-resolution vine size sensors.

The traditional methods discussed in this section for spatially assessing crop load components do not scale up from research settings to commercial ones, where the data needed for high-resolution crop load mapping exceeds the upper limit of the number of samples that may reasonably be collected. However, commercial crop load mapping is feasible with the integration of sensors capable of rapidly collecting high-resolution data that may be used to direct traditional measurements of vine size and yield. In the

following section, new sensing technologies are discussed in terms of their capability to measure and map the components of crop load.

### **Current commercially available enabling technologies for measuring spatial crop load components (vine size and yield).**

Over the past 20 years, new technologies and methodologies to measure yield or vine size have been trialled and, in some cases, commercialised. These new sensors are combined with global navigation satellite systems (GNSS), such as GPS, to ensure data are geo-referenced and can be mapped. Many of these sensors can be incorporated into routine vineyard activities, making the measurement of spatial crop load variation feasible, although it is rarely, if ever, reported.

For crop yield estimation, sensor development is aimed at counting berries and/or clusters during the season although there are currently no commercial ‘on-the-go’ imaging systems available (Nuske et al. 2014, Font et al. 2015, Liu and Whitty 2015, Abdelghafour et al. 2017). Smartphone applications (apps), manually operated, are also emerging to assist berry counting and improve yield estimation (Grossetete et al. 2011, Aquino et al. 2018a) but are not yet widely tested and validated. Commercial yield mapping for yield measurement at-harvest is possible by installing a GNSS-enabled grape yield monitor (GYM) (Advanced Technology Viticulture (ATV), Adelaide, South Australia) on mechanical grape harvesters. Harvest yield maps have been used to help growers audit the current production cycle and establish management plans for subsequent seasons (e.g. Sams et al. 2017). Although designed for harvest use, the ATV GYM has also proved to be effective for mid-season destructive crop estimation with the harvester and for mapping the quantity of crop that is mechanically-thinned (Taylor et al. 2016). As with all yield monitors, correct sensor set-up and calibration is essential to obtain good data. Even so, the yield sensor is subject to some temporal shift in response and should ideally be validated against the crush weight and post-processed if absolute, as opposed to relative, yield patterns are needed (Taylor et al. 2016, Sams et al. 2017).

<< FIGURE 2 HERE >>

Figure 2. An Advanced Viticulture Technology grape yield monitor mounted on a Gregoire harvester in Westfield, NY, USA. Top-left: view down the off-loading discharge conveyor under which the false weighbridge is located. Top-right: Close up showing the externally mounted load cell, protected by a shield, on which the false weighbridge sits to measure mass on the conveyor. Bottom: Location of the sensor system on the discharge conveyor indicated by ellipsoid.

To map vine size, the industry has typically relied on canopy sensing to provide indirect, non-destructive, high spatial resolution canopy measurements. Canopy reflectance in the Visible-Near InfraRed (Vis-NIR) region is a well-established method of estimating vine size (Hall et al. 2002). Typically these canopy sensors return some form of vegetative index (VI) that differentiates larger and smaller vines, and can be used to map spatial patterns of variability in canopy vigour. Commercial services that supply these VI maps in viticulture tend to utilise remote systems, such as satellite platforms (e.g. Oenoview, Groupe ICV, Montpellier, France) or aerial platforms (e.g. Specterra Services Pty. Ltd., Leederville, Western Australia). Terrestrial systems are also available (e.g. Greenseeker, Trimble Agriculture, Sunnydale, CA, USA; CropCircle, HollandScientific, NE, USA) and tend to be adopted by individuals or companies for private use. Unmanned aerial vehicles are a rapidly developing as an alternative platform for canopy sensing (Matese et al. 2015) and may be operated privately or as a contracted service. Smartphone apps have also been used to provide objective in-season vine size information at a site (De Bei et al. 2016, Orlando et al. 2016) but also have not been widely tested or validated to date.

Regardless of the platform on which an optical Vis-NIR sensor is mounted, a VI is not a direct measurement of vine size. It only provides information on the *relative* variation (illustrated in Fig. 3). To properly map vine size, calibration is needed to transform the *relative* VI to an *absolute* vine size metric.

Dormant PM measurements, for example, have been used to calibrate VIs to vine size (Dobrowski et al. 2003, Johnson et al. 2003, Taylor et al. 2017). However, calibrations tend to be site-specific and are non-transferable between sensors or production systems (Taylor et al. 2017). Commercial VI mapping services are available. However, services to translate the VI into useful and practical information, such as PM or LAI, are generally lacking, probably because of the on-ground effort required and the temporal disconnect between canopy sensing (mid-growing season) and pruning operations (during dormancy).

An alternative commercial sensor for vine size that is not based on canopy reflectance is the Physiocap® (E.R.E.C.A. Ltd, Lyon, France). This is a laser-based imaging system that generates maps of shoot counts, shoot diameter and PM. For PM, the images are taken during the dormant period to determine the amount and thickness of the wood to be pruned. The system is currently offered as a contract service targeted at very high quality, vertical-shoot-positioned vineyards in France or it is available for purchase outright (Prof. Bruno Tisseyre, SupAgro Montpellier, *pers. comm.*).

<< FIGURE 3 HERE >>

Figure 3. Relative variation in photosynthetically active biomass in images (right) shown by red arrows to correspond to areas of high, medium, and low sensor response in map (left). (Photo courtesy of L.L. Haggerty, formerly Cornell Cooperative Extension).

The combination of GNSS and new sensing technologies capable of measuring vine yield and indicators of vine size over the past two decades has enabled the spatial characterisation of crop load components. Evidence of the spatial variability of the vine size and yield should exist in the literature given the emergence of sensing technologies and the need to calibrate and validate the sensors against traditional viticulture metrics. The following section will review knowledge in this area.

**Spatial variability in vine size, yield and crop load**

The spatial variability of crop load may be greater or less than the variation exhibited by its components (i.e. interactions between vine size and crop yield may have a dampening or multiplicative effect on crop load variance). Identifying the magnitude and the spatial structure of variability in crop load must be the first step when making crop load management decisions. A direct review of the spatial variability in crop load in vineyards is not possible as no published material was found. Some articles have reported individual source and sink components within the same paper (Tisseyre et al. 2008, Urretavizcaya et al. 2017, Ledderhof et al. 2017) but did not report on spatial crop load metric analysis. An understanding of the reported spatial variance in its components is therefore needed to generate a more ubiquitous understanding of spatial crop load variation.

The magnitude of variation in production must be considered in tandem with its spatial structure, represented as the largest average area of autocorrelation. It is impossible to spatially manage a large magnitude of variation expressed as random noise. Vineyards with large areas of high and low values that exhibit smooth transitions between areas make management decisions and the operation of these decisions much easier (Pringle et al. 2003, Tisseyre and McBratney 2008). Spatial approaches, like the correlogram or variogram, should be used instead of classical statistics of variance to describe spatial variation in vine size and yield. Unfortunately, spatial variation is seldom reported, with the coefficient of variation (CV) the most common statistic reported in precision viticulture and precision agriculture studies.

An investigation using spatial statistics of yield variation in Australian and European systems was performed by Taylor et al. (2005). It showed that it was the magnitude of yield variation that made European vineyards suitable candidates for site-specific vineyard management, while the well organised spatial structure of yield variation in Australian vineyards provided the main opportunity to apply PV. Unfortunately, data were only reported as regional averages, not as individual blocks. These data are in Table 1 along with data from other published studies that have reported some form of statistics in yield

variance for vineyard blocks. Table 1 illustrates that significant yield variance occurs in all reported vineyards (ranges typically  $> 10$  t/ha and CV  $> 20\%$ ) regardless of the location.

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**Table 1. Reported statistics of spatial variance in grape yield variance (NR: not reported). The data from Taylor et al. 2005 are average values from multiple vineyards. Other papers report vineyard block statistics.**

	Country of Origin	Area (ha)	Yield Range (t/ha)	CV (%)	Variogram Parameters		
					Sill Variance	Nugget Variance	Range
					$C_1$ (t/ha) <sup>2</sup>	$C_0$ (t/ha) <sup>2</sup>	$r(m)$
<b>Pringle et al. 2003</b>	Australia	14	NR	32‡	69.8	29.6	145.5
	2	NR	21‡	3.4	20.6	24.2	
	6	NR	34‡	80.3	20.9	1000	
<b>Ortega et al. 2003</b>	Chile	3.0	4.6-46.9††	43	NR	NR	NR
	7.6	0.1-9.0††	60	NR	NR	NR	
<b>Bramley and Hamilton 2004</b>	Australia	3.6	<1 - >16†¶	NR	NR	NR	NR
	7.3	<2 - >17.5†¶	NR	NR	NR	NR	
<b>Arnó, et al. 2005</b>	Spain	5.0	<5-25†¶	41-49§	17-28	14-50	56-73
	8.3	<5-25†¶	20	12	26	44	
<b>Taylor et al. 2005§</b>	Australia, France, Spain	1.5-7.4	NR	22-51 17-37‡	NR	NR	68-159
<b>Tisseyre et al. 2008</b>	France	1.2	NR	26.5§	NR	NR	NR
<b>Bramley et al. 2011a</b>	New Zealand	5.9	7-15¶	NR	NR	NR	NR
<b>Arnó, et al. 2012</b>	Spain	5.0	0 – 28¶	36	NR	NR	NR
<b>Baluja et al. 2012</b>	Spain	2.2	0.5-10.7	67.9	0.35	2.17	146.9
<b>Ledderhof et al. 2017††</b>	Canada	0.4-1.0	0.4-22.7	29-65	NR	NR	NR

† Range taken from yield map legend | ‡ CV<sub>a</sub> Areal coefficient of variation | § range over multiple years of study: yield monitor data | ††: manually sampled data over 4 blocks and 2 years.

Literature where statistics on the spatial variation in vine size are directly reported are rare (Table 2). This is likely because vine size measurements are labour intensive to gather with sufficient density to allow for spatial analysis. When CVs for PM on a per vine measurement have been reported (Table 2), they have consistently been in the range of 39% - 57% regardless of location or the type of viticultural system. The CV of Tisseyre et al. (2008) was lower (13%) however this was a value averaged over 5 vines, which is likely to have removed the stochastic vine-to-vine variance which has been reported as high as 80% of total variance (Taylor and Bates 2012).

High-resolution studies involving LAI measurements tend to be reported as part of a calibration procedure for multi-spectral imaging studies as opposed to stand-alone assessments of vine size as for the PM studies above. Two studies were found with defined sample densities (Table 2); both reported similar ranges in observed LAIs within a vineyard ( $0.2 - 2.8 \text{ m}^2\text{m}^{-2}$ ) but did not report CV or variance.



**Table 2. Reported statistics of spatial variance in vine size as pruning mass or leaf area index (NR: not reported)**

	Area (ha)	Sample (n)	Pruning Mass Range (kg/m)	Leaf Area Range (m <sup>2</sup> m <sup>-2</sup> )	CV (%)	Variogram Parameters		
						Sill Variance	Nugget Variance	Range r (m)
						C <sub>1</sub> (kg/m) <sup>2</sup>	C <sub>0</sub> (kg/m) <sup>2</sup>	
<b>Johnson et al. 2003</b>	800	16 sites of 3-6 vines	NR	0.4-2.8	NR	NR	NR	NR
<b>Tisseyre et al. 2008§</b>	1.2	30	0.69 – 0.91	NR	13.0	NR	NR	NR
<b>Baluja et al. 2012</b>	2.2	67	0.01-0.07	NR	45.1	2.76x10 <sup>4</sup>	4.96x10 <sup>6</sup>	119
<b>López-Lozano and Casterad 2013</b>	2.0	20	NR	0.2-2.2	NR	NR	NR	NR
<b>Taylor and Bates 2013</b>	0.93	1147	0.055-1.283§	NR	47-57§	0.0078-0.0092	0.0386-0.0461	29.22-35.70
<b>King et al. 2014</b>	20	90	0.3-1.7†‡	NR	NR	NR	NR	NR
<b>Ledderhof et al. 2017††</b>	0.7	84	0.05-1.23	NR	39.0-57.2	NR	NR	NR

†Range taken from plot legend | ‡ units converted | § mean annual values and mean CV over 7 years | ††: manually sampled data over 4 blocks and 2 years

Ledderhof et al. (2017) reported CVs for crop load ranging from 45.0% to 84.2% in one growing season in four Pinot Noir vineyards (0.4 – 1.0 ha) in Ontario, Canada. That is the only known study to directly characterize crop load variation. In a 0.7 ha vineyard, yield variation (CV = 38.5%) and vine size variation (CV = 39.4%) interacted to generate markedly greater crop load variation (CV = 84.2%) (Ledderhof et al. 2017). Those findings demonstrated the potential for variation in yield and vine size to have a multiplicative effect on variation in crop load. Though only one study, the results indicated that crop load can drastically vary within vineyards. The literature (Tables 1 and 2) supports this with the spatial variance in both vine size and yield components known to vary considerably in vineyards. Based on the information aggregated in this section, variance in one component of crop load does not tend to dwarf the other, i.e. both exhibit similar CVs, and spatial variance in both vine size and yield is likely to be affecting the spatial variance in crop load.

### **Temporal variability in vine size and yield (crop load components)**

Understanding the spatial variability in vine size, yield and crop load is only useful if the variability also exhibits a temporal stability. Temporal stability may be either inter- or intra-seasonal in nature, and both have implications for differential management. If spatial patterns are temporally stable between years (inter-seasonal), then this limits the need for regular surveys and permits producers to plan ahead with confidence. If within-season (intra-seasonal) spatial patterns are stable, but inter-seasonal spatial patterns are not, then annual early to mid-season sensing (and validation) is needed for in-season crop load management. Effective differential management will be very difficult to implement if spatial patterns exhibit both inter- and intra-seasonal (spatio?)temporal variability.

Inter-annual patterns of variability appear to be stable in the short-term for yield (Tisseyre et al. 2008), vine size (Tisseyre et al. 2008, Taylor and Bates, 2013) and late-season vegetative indices (Kazmierski et al. 2011). However, patterns do shift over time. In southern France, the recommendation is that vine size should be re-validated at least every 6 years (Tisseyre et al. 2008) and vigour maps generated every 3-5 years (Kazmierski et al. 2011). The strongest correlations for vine size are always between consecutive

years (Tissyere et al. 2008, Taylor and Bates, 2013), which endorses the use of vine size data from a current growing season for crop load management in the following season.

The intra-seasonal stability of vine size variation is crucial to determine if the timing of measurement will impact the magnitude and structure of observed variation and crop load metrics. Several studies (Johnson 2003, Hall et al. 2011, Kazmierski et al. 2011, Taylor et al. 2013) have evaluated the relationship between early and late-season canopy vigour (as an indicator of vine size) using both remote and proximal canopy sensors. All studies reported temporally unstable intra-season spatial patterns in canopy vigour and that early season vigour maps poorly correlated to veraison or harvest vigour maps. These studies support a hypothesis that within-season growth rates are variable within vineyards. Variable growth rates will have potentially major implications for shoot and leaf-thinning operations to manipulate crop load. Since final vine size patterns are inter-seasonally stable, late season measurements from the previous season appear more relevant than early season canopy sensing in dictating current-season variable-rate management of the target vine size.

It is important to note that measurements of vine size may be affected in some production systems by management operations (e.g. canopy hedging and lateral shoot trimming). If hedging is done mid-season, then the effect on crop load measurements is likely to be minimal as the ‘hedged’ canopy is of interest. However, if hedging is done immediately before harvest to facilitate mechanical harvesting, then the majority of the canopy that has contributed to production, and thus important in the crop load determination, was removed. PM is difficult to accurately measure in such situations.

A literature search produced no statistics on the temporal variability in vineyard yield maps, although studies have visually or anecdotally noted that patterns of spatial yield variation carried over from one growing season to the next (Bramley and Lamb 2003, Bramley and Hamilton 2004, Bramley 2005, Arnó et al. 2012). However, while the spatial yield pattern exhibited some temporal stability, average, *absolute* yield values can vary significantly between years, i.e. relative yield is the same across areas, but the

absolute value of 'high' and 'low' yields varies greatly). Inter-annual spatial patterns in grape quality, particularly colour and flavour attributes, have been reported as temporally unstable (Bramley 2005, Baluja et al. 2013). That is, the highest yielding areas have the highest quality in some years while lowest yielding areas have the highest quality in other years. However the harvest patterns of total soluble solids values have been reported to exhibit inter-annual stability (Baluja et al. 2013, Verdugo-Vasquez et al. 2015).

After berry set, intra-annual variation in spatial yield patterns is only likely to occur in the case of extreme weather events (e.g. hail, drought, flood) and is therefore unmanageable. The issues with accurate crop estimation and, more importantly, accurate *spatial* crop estimation have been discussed earlier. On-the-go sensors that can count clusters (even flowers) or berries are in development (e.g. Diago et al. 2015, Mirbod et al. 2016, Aquino et al. 2017) and, with correct use and calibration, may provide users the ability to map yield potential at an early- to mid-season stage, when crop can be adjusted to achieve a desired crop load.

The temporal instability of intra-season canopy vigour patterns appears to be a major limitation to in-season measurement, mapping and management. There is no indication from the literature if early season patterns are inter-annually stable, but the lack of correlation of early-season to late-season measurements may mean early-season patterns do not serve as ample basis for management. Spatially integrating data from yield monitors with late or dormant season spatial measurements of vine size currently offers the most reliable estimation of crop load to guide subsequent management decisions. However, ideally, vine size and potential yield should be obtained in-season, and at an early enough stage to allow differential crop load management. In-season yield estimation is likely to be the first barrier crossed due to (1) trends of current technological efforts and (2) the historical and current need for better crop estimation across the industry.

**Spatial crop load mapping**

Generating a map of crop load involves quantifying vine size and yield with high spatial resolution. The Ravaz Index uses yield from a given season and the PM from the subsequent dormant season to calculate crop load. Grape yield monitors measure the absolute yield at harvest and generate information conducive to crop load mapping. To generate a map of PM with a compatible spatial resolution to yield mapping by manually sampling is impossible on a commercial scale. An alternative is to use the Physiocap® system for direct PM measurements or Vis-NIR sensors to generate relative measurements of canopy vigour that can be calibrated against geo-referenced manual PM samples to generate PM maps (Taylor et al. 2017).

Yield and PM data must occupy the same spatial coordinates and therefore require interpolation to co-locate data. Once yield and PM data are on a common grid, their ratio can be calculated and the estimated crop load mapped. Since crop load variability is dependent on the interaction between yield and vine size, the mapped patterns of crop load variability may not match the patterns of yield or vine size individually. A vineyard that has high yield variability may appear uniform on a crop load map if vine size interacts to diminish variation in crop load. For example, consider two hypothetical vines where yield and vine size are measured. The first vine yielded 5 kg of fruit with a PM of 1 kg. The second vine yielded 10 kg with a PM of 2 kg. Though yield and PM vary, the crop load is 5 in both instances.

An objective of crop load mapping is to improve the spatial and temporal resolution of canopy and crop management decisions. Therefore, a spatial representation of the uncertainty in crop load should accompany the crop load map itself. Errors will occur in crop load estimates from the propagation of errors in yield, manual PM and canopy sensor measurements as well as their geo-location in a vineyard. To have confidence in a decision process, the decision-maker must be able to determine the quality of the spatial crop load information before using it to direct a management plan.

An example of how spatial crop load data could be presented is shown (Figure 5) by generating the Ravaz Index from a yield map and a PM map (Fig. 4). In this example, block kriging has been used to generate a

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2  
3 rasterised yield map (Fig. 4b) from raw yield data (Taylor et al. 2007). The PM map (Fig. 4a) was  
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5 generated by block kriging NDVI values from a proximal canopy sensor and then relating the interpolated  
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7 NDVI values to actual pruning mass measurements at selected sites (typically 20-25) in the vineyard  
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9 (Taylor et al. 2017). The yield data thus contains an estimate of error from the interpolation (the standard  
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11 error of prediction, or kriging variance), while the pruning mass map contains a cumulative error  
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13 associated with the original NDVI interpolation (kriging variance) as well as an error associated with the  
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15 linear calibration between NDVI and actual PM measurements (RMSE). Given these errors, an estimate  
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17 of the total uncertainty in crop load could be generated. Methods to achieve this are poorly defined in the  
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19 literature and here an approach is used, based on the summation of errors, to give a relative uncertainty.  
20  
21 Figure 5 clearly shows that there is spatial patterning in crop load as well as spatial patterns in the relative  
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23 uncertainty. This is a simple example to demonstrate the issue. What is certain is that the industry will  
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25 need clearer methods to determine this uncertainty for use in decision support systems (DSS).  
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35 Figure 4. Crop load component maps from a 14.6 ha Concord vineyard in the Lake Erie Region, NY,  
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37 USA. The pruning mass map (a, left) was generated by regression of the canopy vigour against manual  
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39 pruning mass samples. The yield map (b, right) was generated from a grape yield monitor mounted on the  
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41 grape harvester.  
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48 << FIGURE 5 HERE >>  
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51 Figure 5. Map of spatial variation in crop load calculated using the Ravaz Index (a, left) and uncertainty  
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53 in the crop load map (b, right) in a 14.6 ha Concord vineyard in Westfield, New York. The widespread  
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overcropping (Ravaz Index > 10) of these vines in this year was due to a dry and warm season restricting vine size.

As discussed in the introduction, crop load must always be placed within the local context. The maps presented in Fig 4 are from a juicegrape vineyard, and the points A, B and C show points of interest. Considering only the vine size map Fig 4a – pruning mass), B and C are similar, and A differs. If only the yield map is considered (Fig 4b) A and C are similar and B differs. Precision viticulture research to date has tended to focus on using either a vine size or yield map; so would the response at C be more likely associated with response at A or B? In fact the crop load map shows that C is the unusual condition. Despite differences in vine size and yield, points A and B have similar crop load and both are over-cropped. The maturity profile for B should follow A, not C, despite similar yield levels in B and C. Even though yield is low at Point A, fruit thinning should still have been done. The vines at A are very small and need to be grown (not cropped) for longer-term sustainability. Of course, it may be that the vines are small because this area is not suitable for grapes or needs site amelioration. The maps do not provide reasons for low or high response but do indicate where to look.

While these data (Fig 4-5) are from juicegrape vineyards, similar vine size and yield spatial patterning has been observed in winegrape vineyards (e.g. Bramley et al. 2011b). Again, interpretations will always be local, but it is very likely that the fruit composition at points A, B and C cannot be explained with *only* vine size or *only* yield, but requires a consideration of both and their interaction, i.e. the crop load. This is not to suggest that only the crop load map should be considered. Dry matter accumulation and therefore spatial Brix patterns should be associated with the crop load map, but other grape metabolites will have more complex interactions that will also require consideration of the fruit zone microclimate and canopy architecture

**Known technology and knowledge gaps for commercial crop load mapping**

### ***1- Ability to map yield components:***

Total yield can be mapped at harvest, but the ability to map individual yield components (e.g. the variation in yield accounted for by cluster numbers, berries per cluster and berry mass) cannot be determined at present. Imaging technologies applied in-season appear to be promising for counting berry numbers (e.g. Nuske et al. 2014, Aquino et al. 2018b), clusters (e.g. Font et al. 2015, Abdelghafour et al. 2017), the yield components (Diago et al. 2015) and for determining mean berry diameter on a given day (Mirbod et al. 2016). However, limitations still exist before commercialisation and high-resolution mapping is possible, particularly in terms of accounting for occluded fruit that is unable to be seen by sensors. An alternative would be to use imaging technologies that permit the 'hidden' fruit to be imaged (e.g. using x-ray imaging). Such approaches are currently embryonic in development and have inherent safety risks with commercialisation due to the required wavelengths for employment of such technologies.

### ***2 Which Vegetative Index (VI) and when for what application?***

Alternatives to complement optical Vis-NIR canopy sensing are needed. Viticulture (and agriculture in general) currently has a fairly strong fixation with NDVI, and canopy sensing is often (and wrongfully) synonymously used with NDVI sensing (or mapping). NDVI is useful. However, NDVI was defined for use with the original Landsat satellites in the 1970s based on the bands. Modern sensors image a greater number of different bands, particularly red-edge bands. While NDVI is effective, there are many other VIs that may be better tailored for specific purposes relative to NDVI. For example, canopy sensing has been used for directed crop estimation and directed vine size estimation. Is it sensible to use the same information for both applications? Is it sensible to use information collected at the same time (e.g. veraison) for both applications? Despite other indices or combination of indices being shown to be better than the universal NDVI for estimation of source tissues and for vineyard management (Hall et al. 2008,



Nguy-Robertson et al. 2012), relatively little work has been done with the aim of optimising the timing and choice of VI for specific applications in vineyards.

**3 Improved sensing of vine size and/or photosynthetic capacity**

The Vis-NIR canopy sensors provide a relative vigour indication that can be affected by the way the canopy is trained or presented to the sensor. Therefore, while Vis-NIR canopy sensing is useful, improved methods are still needed for accurate within-season and dormant measurements of vine size.

One possible technology to further characterise canopy size, shape and density are laser scanners or light detection and ranging (LiDAR) sensors (Del-Moral-Martinez 2016, Llorens et al. 2011, Arnó et al. 2013). LiDAR has also been shown to be sensitive to the phenological stage of a grapevine (Rinaldi et al. 2013), but there is currently a technology gap in quantifying the ratio of exposed to internal leaf area. Applications for correlating LiDAR with PM have been explored, but with no methodology on how to convert LiDAR response (impacts/m) to PM (Tagarakis et al. 2013, 2017). The commercial adoption of LiDAR technology will also depend on economical access to off-the-shelf-sensors, user-friendly software for data processing and visualisation and integration with other sensors; such tools have yet to be available for the ‘average’ grower.

Canopy/vine size potential is determined by bud number, shoot counts and shoot length. These fundamental determinants of vine size and LAI could be measured by high-resolution imaging (Baweja et al. 2017, Liu et al. 2017) using low cost cameras, e.g. the Microsoft Kinect system (Marinello et al. 2017) or smartphone apps (Aquino et al. 2015 and 2018a, De Bei et al. 2016). The accessibility, ease of use, improving imaging systems and connectivity of mobile technologies will further drive developments in this area. However, local calibration will still be needed to correct the image output to have practical meaning.

**4 Robotic and autonomous systems**

The development of automated, independent robotic platforms in vineyards will allow technologies to be more easily and economically deployed. There are multiple current projects aimed at developing vineyard robots (e.g. VinBot<sup>2</sup>, GRAPE<sup>3</sup> and VineRobot<sup>4</sup>), with some robotic platforms already commercially available (e.g. Robot Oz<sup>5</sup> and Wall-YE<sup>6</sup>). Robotics will remove or reduce time constraints as robots can be permanently deployed in fields and collect several datasets, even time-consuming point data. Provided the platforms are cost-effective, robotics may enable dense spatio-temporal measurements that would be cost- and labor-prohibitive if done by humans (e.g. ceptomtry). The robotic platforms will require decision systems that direct the robot to an exact location in the vineyard at the desired time so that observations are immediately relevant to management and decision-making. These decision systems are poorly developed at present.

### ***5 Spatial measurement of fruit composition***

The ideal crop load will vary for each unique viticulture system. Mapping crop load is the first and major step to managing Crop load. However, it will be important to understand the relationship between crop load and fruit development and composition. Methods to map attributes associated with fruit quality are therefore needed. Fruit attributes are known to be spatially and temporally variable (e.g. Bramley and Hamilton 2004, Tisseyre et al. 2008). They can currently be taken as point-in-time measurements in vineyards using purpose-built commercial sensors, e.g. the Multiplex Fluorometer (ForceA, Paris, France). However, despite several reported applications in the research literature (Bramley et al. 2011c, Baluja et al. 2012, Pothén and Nuske 2016), on-the-go pre-harvest or on-harvester commercial sensors of fruit composition have yet to be commercialised. It is interesting that only spatial relationships of fruit composition attributes with either yield or vine size (vigour) have been reported (e.g. Bramley and

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<sup>2</sup> <http://vinbot.eu/>

<sup>3</sup> <http://echord.eu/grape/>

<sup>4</sup> <http://www.vinerobot.eu/project/>

<sup>5</sup> <http://www.naio-technologies.com/en/agricultural-equipment/vineyard-weeding-robot/>

<sup>6</sup> <http://wall-ye.com/>

All websites accessed 29/07/2017

Hamilton 2004, Bramley et al. 2011c, Trought and Bramley 2011, Arnó et al. 2012, Tisseyre et al. 2008, Ledderhof et al. 2017) and relationships tend to be weak or temporally variable. To date, spatial fruit composition attributes have not been related to spatial crop load information. Fruit development is certainly complex, particularly for non-sugar attributed. It would be of interest to investigate if a more stable relationship emerged when fruit attributes (particularly non-sugar attributes) were compared to the actual crop load rather than its individual components alone, and to identify the viticulture systems within which this tended to occur.

**6    *Improved vineyard monitoring***

Opportunities exist to either reduce the level of vineyard sampling without diminishing the quality of data, or to increase the quality of collected data with the same sample size by using spatial data to replace random or systematic vineyard sampling schemes. Stratified random sampling approaches have been shown to improve vineyard assessment over point sampling (Bramley 2001, Carrillo et al. 2016, Araya-Alman et al. 2017); however, grower support to achieve proper stratified sampling is often still limited. Smart sampling techniques are not well understood or adopted by the industry. There is a compounding problem that viticulture, like agriculture, is becoming more data rich. Methods for designing stratified sampling approaches will need to become more sophisticated and multivariate in nature as this trend continues. Monitoring systems will also need to have communication and network, particularly Internet of (Agri-) Things, capabilities incorporated.

**7    *Correct data fusion techniques***

Improved and enhanced vineyard monitoring is increasing the (potential) amount of spatio-temporal data that is or can be collected in vineyards on an annual basis. More data are not necessarily better. The development, adoption and application of spatio-temporal data fusion techniques is crucial for progression of spatial crop load mapping and PV in general. In this review, a possible fusion of a yield and vine size maps has been generated, but this example is not considered the optimal approach; it

illustrates the potential, not the final result. Data fusion approaches need to generate sensible spatial outputs, such as a Ravaz Index map, but also the spatial error and uncertainty in the output. Some fusions may be purely quantitative and derived directly from the data. However, vineyard information may also be qualitative in nature and based on human intuition and historical knowledge. Soft-computing in spatial agricultural data has been proposed (Guillaume et al. 2013, Leroux et al. 2018) but has not been widely implemented to date and remains an area that needs addressing to fuse qualitative and quantitative data into a desired information layer.

### ***8 Development of (spatial) decision support systems for effective management.***

Creating information layers (e.g. a map of spatial crop load) is necessary, but effectively managing variation is where the practical value lies. As discussed above, data fusion techniques are necessary but the space within which a spatial decision support system (DSS) will operate also needs to be defined. Is an after-the-fact approach that manages against the previous seasons' validated measurements of spatial vine size and crop yield variation best? Or is a current-season approach that manages against early-season estimations of vine size and/or crop yield better? Perhaps a hybrid approach, where the user compares previous and current-season trends to formulate management decisions, is the best option? Whichever direction is taken, decision systems need to be a) spatial in nature, b) able to operate at high temporal frequencies, c) able to operate in both hard- and soft-computing environments, d) able to operate with both on- and off-vineyard (farm) data and e) adaptable and able to incorporate modelled as well as monitored data sources. It is probable that the evolution of generic spatial agricultural information and decision systems will provide a platform for points a – d (Shahar et al. 2017). The last point (e) identifies the need for effective predictive models in viticulture, which should be addressed by the industry.

### ***9 Training of Viticulture Professionals***

Processing and interpreting spatial data requires a different analytical skill set relative to conventional statistical analysis of viticultural or agricultural field trials. Viticulturists (and agronomists generally) are

not well trained in handling spatial information. Consequently, grower support for PV (and PA) is often limited. A well-organised service industry is key to the successful translation of new technologies (Reichardt and Jürgens 2009). Viticultural knowledge needs to be interfaced with spatial and temporal applications and analyses and higher education institutions need to address this globally.

**Conclusions**

The ability to generate high-resolution yield, vine size and crop load maps is now possible, although technical support services are commercially limited at the moment. crop load mapping is currently most effective when utilising the previous year’s vine size information. The generation of in-season crop load information is more difficult but an area where the development of novel vine size and yield sensors is progressing. When such sensors become available, they are likely to provide better information to support early and mid-season monitoring of crop load.

A review of existing literature showed that there was very little published material on spatial vine size and yield statistics to date and almost no information on spatial crop load. The published material did indicate that the magnitude and spatial structure of within vineyard variability in vine size and yield was significant. It is logical to assume that crop load is also highly variable within vineyards. However, there are still areas where advances in sensor development (e.g. to map fruit attributes and individual yield components, not just yield) are needed to deliver more pertinent information. Advances in data analysis and service support are needed to make spatial crop load mapping a common commercial activity. Despite this, mapping and interpreting yield and/or vine size individually is possible and a move to mapping crop load values (including the error in the maps) is expected to help inform differential management in vineyards.

## References

- Abdelghafour, F., Keresztes, B., Germain, C. and Da Costa, J.P. (2017) Potential of on-board colour imaging for in-field detection and counting of grape bunches at early fruiting stages. *Advances in Animal Biosciences: Precision Agriculture (ECPA) 2017* **8**, 505–509.
- Acevedo-Opazo, C., Jara-Rojas, F., Valdés-Gomez, H., Ortega-Farias, S., Taylor, J.A. and Tisseyre, B. (2011) Towards the spatial prediction model of vine water status using auxiliary information. In: VI International Symposium on Irrigation of Horticultural Crops. *Acta Horticulturae* **889**, 151-158.
- Aquino, A., Millan, B., Gaston, D., Diago, M.-P. and Tardaguila, J. (2015) vitisFlower®: Development and testing of a novel android-smartphone application for assessing the number of grapevine flowers per inflorescence using artificial vision techniques. *Sensors (Switzerland)* **15**, 21204-21218.
- Aquino, A., Diago, M.P., Millán, B. and Tardaguila, J. (2017) A new methodology for estimating the grapevine-berry number per cluster using image analysis, *Biosystems Engineering* **156**, 80-95.
- Aquino, A., Barrio, I., Diago, M.-P., Millan, B. and Tardaguila, J. (2018a) vitisBerry: An Android-smartphone application to early evaluate the number of grapevine berries by means of image analysis. *Computers and Electronics in Agriculture* **148**, 19-28.
- Aquino, A., Millan, B., Diago, M.-P. and Tardaguila, J. (2018b) Automated early yield prediction in vineyards from on-the-go image acquisition. *Computers and Electronics in Agriculture* **144**, 26-36.
- Araya-Alman, M., Acevedo-Opazo, C., Guillaume, S., Valdés-Gómez, H., Verdugo-Vásquez, N., Moreno, Y. and Tisseyre, B. (2017) Using ancillary yield data to improve sampling and grape yield estimation of the current season. *Advances in Animal Biosciences: Precision Agriculture (ECPA) 2017* **8**, 515–519.

- 1  
2  
3 Arnó, J., Bordes, X., Ribes-Dasi, M., Blanco, R., Rosell, J.R. and Esteve, J. (2005) Obtaining grape yield  
4 maps and analysis of within-field variability in Raimat (Spain). Stafford, J.V., ed. Precision  
5 Agriculture '05, Proceedings of the Fifth European Conference on Precision Agriculture; 8-11  
6 June 2005; Uppsala, Sweden (Wageningen Academic Publishers, Wageningen, The Netherlands)  
7 pp. 899-906.  
8  
9  
10  
11  
12  
13 Arnó, J., Martínez-Casasnovas, J.A., Ribes-Dasi, M. and Rosell, J.R. (2009) Review: Precision  
14 Viticulture. Research topics, challenges and opportunities in site-specific vineyard management.  
15 Spanish Journal of Agricultural Research **7**, 779-790.  
16  
17  
18  
19  
20 Arnó, J., Rosell, J.R., Blanco, R., Ramos, M.C. and Martínez-Casasnovas, J.A. (2012) Spatial variability  
21 in grape yield and quality influenced by soil and crop nutrition characteristics. Precision  
22 Agriculture **13**, 393-410.  
23  
24  
25  
26 Arnó, J., Vallès, J.M., Llorens, J., Sanz, R., Masip, J., Palacín, J. and Rosell-Polo, J.R. (2013) Leaf area  
27 index estimation in vineyards using a ground-based LiDAR scanner. Precision Agriculture **14**,  
28 290-306.  
29  
30  
31  
32  
33 Baluja, J., Diago, M.P., Goovaerts, P. and Tardaguila, J. (2012) Assessment of the spatial variability of  
34 anthocyanins in grapes using a fluorescence sensor: Relationships with vine vigour and yield.  
35 Precision Agriculture **13**, 457-472.  
36  
37  
38  
39 Baluja, J., Tardaguila, J., Ayestaran, B. and Diago, M.P. (2013) Spatial variability of grape composition  
40 in a Tempranillo (*Vitis vinifera* L.) vineyard over a 3-year survey. Precision Agriculture **14**, 40–  
41 58.  
42  
43  
44  
45 Bates, T. (2006) Crop Load management in western New York. Wine East, Nov-Dec, pp. 10-19.  
46  
47 Bates, T. (2008) Pruning level affects growth and yield of New York Concord on two training systems.  
48 American Journal of Enology and Viticulture **59**, 276-286.  
49  
50  
51 Baweja, H.S., Parhar, T. and Nuske, S. (2017) Early-season Vineyard Shoot and Leaf Estimation Using  
52 Computer Vision Techniques. Proceedings of the 2017 ASABE Annual International Meeting;  
53 16-19 July 2017; Spokane, Washington, USA, Article No. 1700349.  
54  
55  
56  
57  
58  
59  
60

- Bongiovanni, R. and Lowenberg-Deboer, J. (2004) Precision agriculture and sustainability. *Precision Agriculture* **5**, 359-387.
- Bravdo, B., Hepner, Y., Loinger, C., Cohen, S. and Tabacman, H. (1985) Effect of crop level and crop load on growth, yield, must and wine composition of Cabernet Sauvignon. *American Journal of Enology and Viticulture* **36**, 125-131.
- Bramley, R.G.V. (2001) Vineyard sampling for more precise, targeted management. Proceedings of the first National Conference on Geospatial Information & Agriculture, Sydney, NSW, Australia (Causal Productions: Sydney) pp. 417-27.
- Bramley, R.G.V. (2005) Understanding variability in winegrape production systems 2. Within vineyard variation in quality over several vintages. *Australian Journal of Grape and Wine Research* **11**, 33-42.
- Bramley, R.G.V. and Hamilton, R. (2004) Understanding variability in winegrape production systems 1. Within vineyard variation in yield over several vintages. *Australian Journal of Grape and Wine Research* **10**, 32-45.
- Bramley, R.G.V. and Lamb, D.W. (2003) Making sense of vineyard variability in Australia. Ortega, R. and Esser, A., eds. *Precision Viticulture Symposium. Proceedings of an International Symposium held as part of the IX Congreso Latinoamericano de Viticultura y Enologia*; 24-28 November 2003; Santiago, Chile pp. 35-54.
- Bramley, R.G.V. and Proffitt, A.P.B. (1999) Managing variability in viticultural production. *The Australian Grapegrower and Winemaker* **427**, 11-16.
- Bramley, R.G.V., Trought, M.C.T. and Praat, J.P. (2011a) Vineyard variability in Marlborough, New Zealand: characterising variation in vineyard performance and options for the implementation of Precision Viticulture. *Australian Journal of Grape and Wine Research* **17**, 72-78.
- Bramley, R.G.V., Ouzman, J. and Boss, P.K. (2011b) Variation in vine vigour, grape yield and vineyard soils and topography as indicators of variation in the chemical composition of



- grapes, wine and wine sensory attributes. Australian Journal of Grape and Wine Research **17**, 217–229.
- Bramley, R.G.V., Le Moigne, M., Evain, S., Ouzman, J., Florin, L., Fadaili, E.M., Hinze, C.J. and Cerovic, Z.G. (2011c). On-the-go sensing of grape berry anthocyanins during commercial harvest – Development and prospects. Australian Journal of Grape and Wine Research **17**, 316-326.
- Carrillo, E., Matese, A., Rousseau, J. and Tisseyre, B. (2016). Use of multi-spectral airborne imagery to improve yield sampling in viticulture. Precision Agriculture **17**, 74-92.
- Clingeffer, P., Dunn, G.M., Krstic, M. and Martin, S. (2001) Crop development, crop estimation and crop control to secure quality and production of major wine grape varieties: A national approach: final report to Grape and Wine Research and Development Corporation. Grape and Wine Research and Development Corporation: Adelaide, SA, Australia.
- Coombe, B.G. and Dry, P.R. (2005) Viticulture Volume 1: Resources, 2<sup>nd</sup> Ed. (Winetitles: Adelaide, South Australia) pp 90-92.
- Coombe, B.G. and Dry, P.R. (2006) Viticulture Volume 2: Practices, 2<sup>nd</sup> Ed. (Winetitles: Adelaide, South Australia) pp 72.
- Dami, I. (2006) Methods of Crop Estimation in Grapes. Dept. Horticulture and Crop Science OARDC-The Ohio State University. <http://i3dviticulture.pbworks.com/f/CropYieldEstimationMethods.pdf>. [accessed 05/06/2018]
- De Bei, R., Fuentes, S., Gilliam, M., Tyerman, S., Edwards, E., Bianchini, N., Smith, J. and Collins, C. (2016) VitiCanopy: A Free Computer App to Estimate Canopy Vigor and Porosity for Grapevine. Sensors **16**, 585.
- Del-Moral-Martínez, I., Rosell-Polo, J.R., Sanz, R., Masip, J., Martínez-Casasnovas, J.A. and Arnó, J. (2016) Mapping Vineyard Leaf Area Using Mobile Terrestrial Laser Scanners: Should Rows be Scanned On-the-Go or Discontinuously Sampled? Sensors **16**, 119.

- Diago, M.P., Tardaguila, J., Aleixos, N., Millan, B., Prats-Montalban, J. M., Cubero, S. and Blasco, J. (2015) Assessment of cluster yield components by image analysis. *Journal of the Science of Food and Agriculture* **95**, 1274-1282.
- Dokoozlian, N.K. and Kliewer, W.M. (1995) The light environment within grapevine canopies. I. Description and seasonal changes during fruit development. *American Journal of Enology and Viticulture* **46**, 209-217.
- Dobrowski, S.Z., Ustin, S.L. and Wolpert, J.A. (2003) Grapevine dormant pruning weight prediction using remotely sensed data. *Australian Journal of Grape and Wine Research* **9**, 177-182.
- Dunn, G.M. (2010). Fact sheet: Yield forecasting. GWRDC, South Australia, Australia.
- Font, D., Tresanchez, M., Martínez, D., Moreno, J., Clotet, E. and Palacín, J. (2015) Vineyard yield estimation based on the analysis of high resolution images obtained with artificial illumination at night. *Sensors* **15**, 8284-8301.
- Grossetete, M., Berthoumieu, Y., Da Costa, J.-P., Germain, C., Lavialle, O. and Grenier, G. (2011) A new approach on Early Estimation of Vineyard Yield: Site specific counting of berries by using a Smartphone. Stafford, J.V., ed. *Precision Agriculture 2011: papers presented at the Eighth European Conference on Precision Agriculture 2011; 11-14 July 2011; Prague, Czech Republic* (Czech Centre for Science and Society) 8 p.
- Guillaume, S., Charnomordic, B., Tisseyre, B. and Taylor, J. (2013) Soft computing-based decision support tools for spatial data. *International Journal of Computational Intelligence Systems* **6**, 18-33.
- Hall, A., Lamb, D., Holzapfel, B. and Louis, J. (2002) Optical remote sensing applications in viticulture - A review. *Australian Journal of Grape and Wine Research* **8**, 36-47.
- Hall, A., Louis, J.P. and Lamb D.W. (2008) Low-resolution remotely sensed images of winegrape vineyards map spatial variability in planimetric canopy area instead of leaf area index. *Australian Journal of Grape and Wine Research* **14**, 9-17.

- Hall, A., Lamb, D.W., Holzapfel, B.P. and Louis, J.P. (2011) Within-season temporal variation in correlations between vineyard canopy and winegrape composition and yield. *Precision Agriculture* **12**, 103-117.
- Howell, G.S. (2001) Sustainable grape productivity and the growth yield relationship: A review. *American Journal of Enology and Viticulture* **52**, 165-174.
- Johnson, L.F. (2003) Temporal stability of an NDVI-LAI relationship in a Napa Valley vineyard. *Australian Journal of Grape and Wine Research* **9**, 96-101.
- Johnson, L.F., Roczen, D.E., Youkhana, S.K., Nemani, R.R. and Bosch, D.F. (2003) Mapping vineyard leaf area with multispectral satellite imagery. *Computers and Electronics in Agriculture* **38**, 33-44.
- Kazmierski, M., Glémas, P., Rousseau, J. and Tisseyre, B. (2011) Temporal stability of within-field patterns of NDVI in non irrigated Mediterranean vineyards. *Journal International des Sciences de la Vigne et du Vin* **45**, 61-73.
- Keller, M., Mills, L.J., Wample, R.L. and Spayd, S.E. (2004) Crop load management in Concord grapes using different pruning techniques. *American Journal of Enology and Viticulture* **55**, 35-50.
- Kicherer, A., Klodt, M., Sharifzadeh, S., Cremers, D., Töpfer, R. and Herzog, K. (2017) Automatic image-based determination of pruning mass as a determinant for yield potential in grapevine management and breeding. *Australian Journal of Grape and Wine Research* **23**, 120-124.
- King, P., Smart, R.E. and McClellan, D.J. (2014) Within-vineyard variability in vine vegetative growth, yield, and fruit and wine composition of Cabernet Sauvignon in Hawke's Bay, New Zealand. *Australian Journal of Grape and Wine Research* **20**, 234-246.
- Kliewer, W.M. and Dokoozlian, N.K. (2005) Leaf area / crop weight ratios of grapevines: influence on fruit composition and wine quality. *American Journal of Enology and Viticulture* **56**, 170-181.
- Leroux, C., Jones, H., Pichon, L., Guillaume, S., Lamour, J., Taylor, J., Naud, O., Crestey, T., Lablee, J.-L. and Tisseyre, B. (2018) GeoFIS: An Open Source, Decision-Support Tool for Precision Agriculture Data. *Agriculture* **8**, p73.

- Liu, S. and Whitty, M. (2015) Automatic grape bunch detection in vineyards with an SVM classifier. *Journal of Applied Logic* **13**, 643-653.
- Liu, S., Cossell, S., Tang, J., Dunn, G. and Whitty, M. (2017) A computer vision system for early stage grape yield estimation based on shoot detection. *Computers and Electronics in Agriculture* **137**, 88-101.
- Ledderhof, D., Reynolds, A.G., Brown, R. and Jollineau, M. (2017) Spatial variability in ontario pinot noir vineyards: use of geomatics and implications for precision viticulture. *American Journal of Enology and Viticulture* **68**, 151-168.
- Llorens, J., Gil, E., Llop, J. and Escolà, A. (2011) Ultrasonic and LIDAR Sensors for Electronic Canopy Characterization in Vineyards: Advances to Improve Pesticide Application Methods. *Sensors* **11**, 2177-2194.
- López-Lozano, R. and Casterad, M.A. (2013) Comparison of different protocols for indirect measurement of leaf area index with ceptometers in vertically trained vineyards. *Australian Journal of Grape and Wine Research* **19**, 116-122.
- Marinello, F., Pezzuolo, A., Meggio, F., Martínez-Casasnovas, J.A., Yezekyan, T. and Sartori, L. (2017) Application of the Kinect sensor for three dimensional characterization of vine canopy. *Advances in Animal Biosciences: Precision Agriculture (ECPA) 2017* **8**, 525-529.
- Matese, A., Toscano, P., Di Gennaro, S.F., Genesio, L., Vaccari, F.P., Primicerio, J., Belli, C., Zaldei, A., Bianconi, R. and Gioli, B. (2015) Intercomparison of uav, aircraft and satellite remote sensing platforms for precision viticulture. *Remote Sensing* **7**, 2971-2990.
- McDonnell, C., Dry, P.R., Wample, R.L. and Bastian, S. (2008) The effect of crop load and extended ripening on vine balance and wine quality in Cabernet Sauvignon. *Proceedings of the Second Annual National Viticulture Research Conference; 9-11 July 2008; Davis, California, USA.* pp. 49-50.

- Meyers, J.M. and Vanden Heuvel, J.E. (2008) Enhancing the precision and spatial acuity of point quadrat analysis via calibrated exposure mapping. *American Journal of Enology and Viticulture* **59**, 425-431.
- Mirbod, O., Yoder, L. and Nuske, S. (2016) Automated Measurement of Berry Size in Images. *IFAC-PapersOnLine* **49**, 79-84.
- Naor, A., Gal, Y. and Bravdo, B. (2002) Shoot and cluster thinning influence vegetative growth, fruit yield, and wine quality of 'Sauvignon blanc' grapevines. *Journal of the American Society for Horticulture Science* **127**, 628-634.
- Nguy-Robertson, A., Gitelson, A., Peng, Y., Viña, A., Arkebauer, T. and Rundquist, D. (2012). Green Leaf Area Index Estimation in Maize and Soybeans: Combining Vegetation Indices to Achieve Maximal Sensitivity. *Agronomy Journal* **104**, 136-1347.
- Nuske, S., Wilshusen, K., Achar, S., Yoder, L., Narasimhan, S. and Singh, S. (2014) Automated visual yield estimation in vineyards. *Journal of Field Robotics* **31**, 837-860.
- Orlando, F., Movedi, E., Coduto, D., Parisi, S., Brancadoro, L., Pagani, V., Guarneri, T. and Confalonieri, R. (2016). Estimating Leaf Area Index (LAI) in Vineyards Using the Pocket LAI Smart-App. *Sensors* **16**, 2004.
- Ortega, R., Esser, A. and Santibanez, O. (2003) Spatial variability of wine grape yield and quality in Chilean vineyards: economic and environmental impacts. Stafford, J.V. and Werner, A., eds. *Precision Agriculture '03. Proceedings of the Fourth European Conference on Precision Agriculture*; 15-17 June 2003; Berlin, Germany (Wageningen Academic Publishers, Wageningen, The Netherlands) pp. 499-506.
- Pothen, Z. and Nuske, S. (2016) Automated Assessment and Mapping of Grape Quality through Image-based Color Analysis. *IFAC-PapersOnLine*, **49**, 16
- Partridge, N.L. (1925) The use of the growth-yield relationship in field trials with grapes. *Journal of the American Society for Horticulture Science* **23**, 84-87.

- Petrie, P.R. and Clingeleffer, P.R. (2006) Crop thinning (hand versus mechanical), grape maturity and anthocyanin concentration: outcomes from irrigated Cabernet Sauvignon (*Vitis vinifera* L.) in a warm climate. *Australian Journal of Grape and Wine Research* **12**, 21-29.
- Pringle, M.J., McBratney, A.B., Whelan, B.M. and Taylor, J.A. (2003) A preliminary approach to assessing the opportunity for site-specific crop management in a field, using yield monitor data. *Agricultural Systems* **76**, 273-292.
- Ravaz, M.L. (1911) L'effeuillage de la vigne. *Annales d L'Ecole Nationale d'agriculture de Montpellier* **11**, 216-244.
- Reichardt, M. and Jürgens, C. (2009) Adoption and future perspective of precision farming in Germany: results of several surveys among different agricultural target groups. *Precision Agriculture* **10**, 73-94.
- Rinaldi, M., Llorens, J. and Gil, E. (2013) Electronic characterization of the phenological stages of grapevine using a LIDAR sensor. Stafford, J.V., ed. *Precision Agriculture '13. Proceedings of the Ninth European Conference on Precision Agriculture*; 7-11 July 2013; Lleida, Spain (Wageningen Academic Publishers: Wageningen, Netherlands) pp. 603-609.
- Sams, B., Litchfield, C., Sanchez, L. and Dokoozlian, N. (2017) Two methods for processing yield maps from multiple sensors in large vineyards in California. *Advances in Animal Biosciences: Precision Agriculture (ECPA) 2017* **8**, 530–533.
- Santesteban, L.G., Miranda, C. and Royo, J. B. (2010) Vegetative Growth, Reproductive Development and Vineyard Balance. In *Methodologies and Results in Grapevine Research*, in Delrot, S., Medrano, H., Or, E., Bavaresco, L., and Grando, S. (eds). (Springer: Netherlands) pp 45–56.
- Shahar, Y., Blacker, C., Kavanagh, R., James, P. and Taylor J.A. (2017) Implementation of Ag Data Agricultural Services for Precision Agriculture. *Advances in Animal Biosciences: Precision Agriculture (ECPA) 2017*, **8**, 656-661.
- Shaulis, N., Jordan, T.D. and Tompkins, J.P. (1966) Cultural practices for New York vineyards. Cornell Ext. Bulletin No. 805.

- Shaulis, N. and Steel, R.D. (1969) The interaction of resistant rootstock to the nitrogen, weed control, pruning, and thinning on the productivity of Concord grapevines. *Journal of the American Society of Horticultural Science* **91**, 122-129.
- Smart, R.E. and Robinson, M. (1991) *Sunlight into Wine. A Handbook for Winegrape Canopy Management*. (Winetitles: Adelaide, Australia).
- Tagarakis, A., Liakos, V., Chatzinikos, T., Koundouras, S., Fountas, S. and Gemtos, T. (2013) Using laser scanner to map pruning wood in vineyards. Stafford, J.V., ed., *Precision Agriculture '13. Proceedings of the Ninth European Conference on Precision Agriculture*; 7-11 July 2013; Lleida, Spain (Wageningen Academic Publishers: Wageningen, Netherlands) pp. 633-639.
- Tagarakis, A., Koundouras, S., Fountas, S. and Gemtos, T. (2017) Evaluation of the use of LIDAR laser scanner to map pruning wood in vineyards and its potential for management zones delineation. *Precision Agriculture* **19**, 334-347.
- Taylor, J., Tisseyre, B., Bramley, R. and Reid, A. (2005) A comparison of the spatial variability of vineyard yield in European and Australian production systems. Stafford, J.V., ed. *Precision Agriculture '05. Proceedings of the Fifth European Conference on Precision Agriculture*; 8-11 June 2005; Uppsala, Sweden (Wageningen Academic Publishers, Wageningen, The Netherlands) pp. 907-914.
- Taylor, J.A., McBratney, A.B. and Whelan, B.M. (2007) Establishing management classes for broadacre grain production. *Agronomy Journal* **99**, 1366-1376.
- Taylor, J.A. and Bates, T.R. (2013) Temporal and spatial relationships of vine pruning mass in Concord grapes. *Australian Journal of Grape and Wine Research* **19**, 401-408.
- Taylor, J., Nuske, S., Singh, S., Hoffman, J. and Bates, T. (2013) Temporal evolution of within-season vineyard canopy response from a proximal sensing system. Stafford, J.V., ed. *Precision Agriculture '13. Proceedings of the Ninth European Conference on Precision Agriculture*; 7-11 July 2013; Lleida, Spain (Wageningen Academic Publishers, Wageningen, The Netherlands) pp. 659-665.

- Taylor, J.A., Sanchez, L., Sams, B., Haggerty, L., Jakubowski, R., Djafour, S. and Bates, T.R. (2016) Evaluation of a grape yield monitor for use mid-season and at harvest. *Journal International des Sciences de la Vigne et du Vin* **50**, 57-63.
- Taylor, J.A., Link, K., Taft, T., Jakubowski, R., Joy, P., Martin, M., Hoffman, J., Jankowski, J. and Bates, T.R. (2017). A protocol to map vine size in commercial single high-wire trellis vineyards using 'off-the-shelf' proximal canopy sensing systems. *Catalyst* **2**, 35-47.
- Tisseyre, B., Ojeda, H. and Taylor, J. (2007) New technologies and methodologies for site-specific viticulture. *Journal International des Sciences de la Vigne et du Vin* **41**, 63-76.
- Tisseyre, B., Mazzoni, C. and Fonta, H. (2008) Within-field temporal stability of some parameters in viticulture: Potential toward a site specific management. *Journal International des Sciences de la Vigne et du Vin* **42**, 27.
- Tisseyre, B. and McBratney A.B. (2008). A technical opportunity index based on mathematical morphology for site-specific management: An application to viticulture. *Precision Agriculture* **9**, 101–113.
- Trought, M.C.T. and Bramley, R.G.V (2011) Vineyard variability in Marlborough, New Zealand: Characterising spatial and temporal changes in fruit composition and juice quality in the vineyard. *Australian Journal of Grape and Wine Research* **17**, 72-82.
- Trought, M.C.T., Dixon, R., Mills, T., Greven, M., Agnew, R., Mauk, J.L. and Praat, J.P. (2008) The impact of differences in soil texture within a vineyard on vine vigour, vine earliness and juice composition. *Journal International des Sciences de la Vigne et du Vin* **42**, 67-72.
- Urretavizcaya, I., Royo, J.B., Miranda, C., Tisseyre, B., Guillaume, S. and Santesteban, L.G. (2017) Relevance of sink-size estimation for within-field zone delineation in vineyards. *Precision Agriculture* **18**, 133-144.
- Verdugo-Vásquez, N., Acevedo-Opazo, C., Valdés-Gómez, H., Ingram, B., García de Cortázar, I. and Tisseyre, B. (2015) Temporal stability of within-field variability for total soluble solids in four irrigated grapevines cultivars growing under semi-arid conditions. Stafford, J.V., ed., *Precision*



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Agriculture '15, Proceedings of the Tenth European Conference on Precision Agriculture; 12-16 July; Volcani Center, Israel (Wageningen Academic Publishers, Wageningen, The Netherlands) pp. 111-129.

Whelan, B.M. and McBratney, A.B. (2000) The “Null Hypothesis” of Precision Agriculture Management. Precision Agriculture **2**, 265-279.

Winkler, A.J. (1954) Effects of Overcropping. American Journal of Enology and Viticulture **5**, 4-12.

Winkler, A.J., Cook, J.A., Kliewer, W.M., and Lider, L.A. (1974) General Viticulture. (University of California Press : Berkeley, California). pp 300.

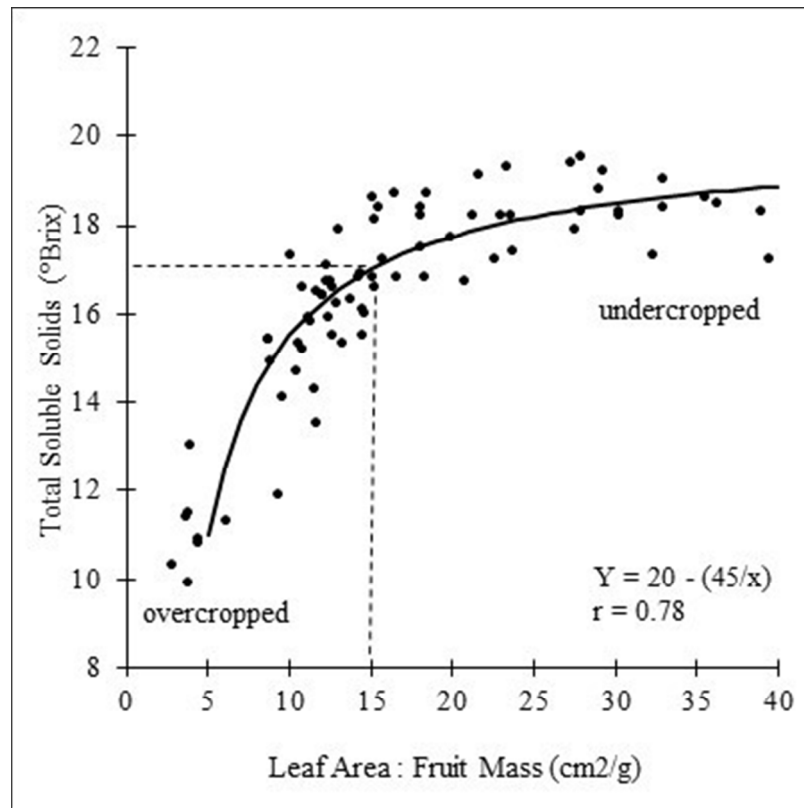


Figure 1. The influence of crop load, expressed as a leaf area to fruit mass ratio, on total soluble solids (°Brix) at harvest in Concord (*Vitis labruscana* cv. Bailey) vines in the Lake Erie viticulture region (Latitude 42.4°N). Leaf area was measured at maximum canopy fill and fruit mass and °Brix were measured at harvest. Optimum level of total soluble solids at harvest (17 °Brix) was reached when leaf area is balanced with fruit mass at a ratio of 15 cm<sup>2</sup> g<sup>-1</sup>. Lower values lead to immature fruit while higher values could have ripened more fruit without any effect on quality (°Brix) premiums.

84x85mm (120 x 120 DPI)



Figure 2. An Advanced Viticulture Technology grape yield monitor mounted on a Gregoire harvester in Westfield, NY, USA. Top-left: view down the off-loading discharge conveyor under which the false weighbridge is located. Top-right: Close up showing the externally mounted load cell, protected by a shield, on which the false weighbridge sits to measure mass on the conveyor. Bottom: Location of the sensor system on the discharge conveyor indicated by ellipsoid.

75x95mm (96 x 96 DPI)

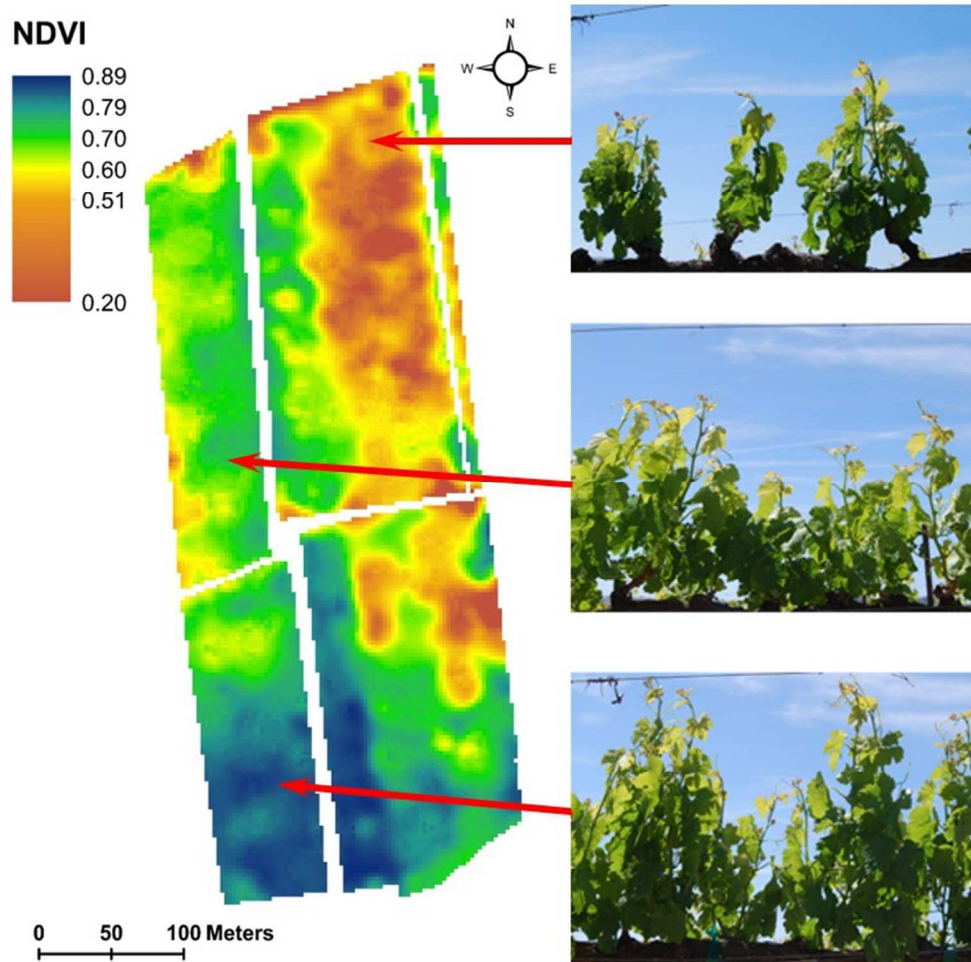


Figure 3. Relative variation in photosynthetically active biomass in images (right) shown by red arrows to correspond to areas of high, medium, and low sensor response in map (left). (Photo courtesy of L.L. Haggerty, formerly Cornell Cooperative Extension).

227x219mm (96 x 96 DPI)

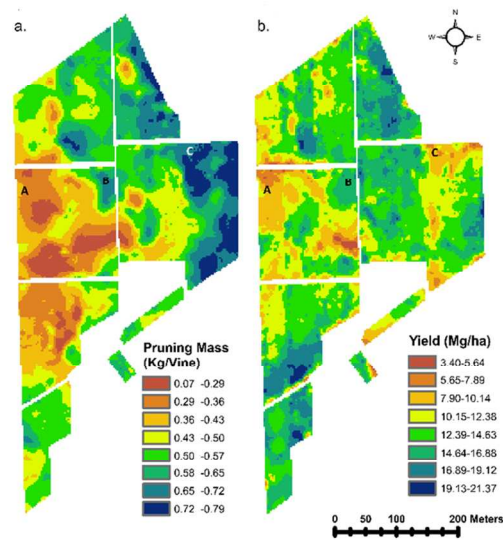


Figure 4. Crop load component maps from a 14.6 ha Concord vineyard in the Lake Erie Region, NY, USA. The pruning mass map (a, left) was generated by regression of the canopy vigour against manual pruning mass samples. The yield map (b, right) was generated from a grape yield monitor mounted on the grape harvester.

338x190mm (96 x 96 DPI)

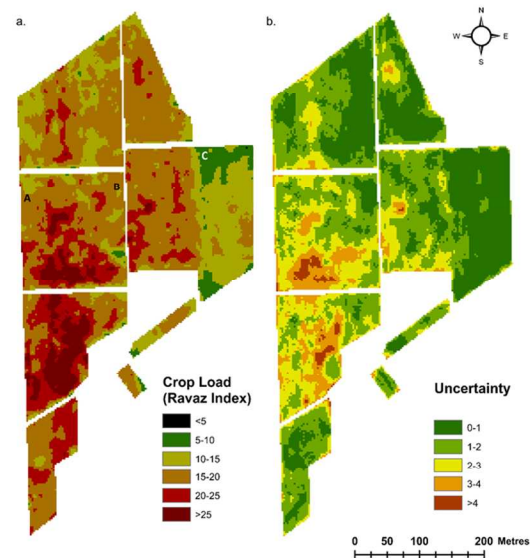


Figure 5. Map of spatial variation in crop load calculated using the Ravaz Index (a, left) and uncertainty in the crop load map (b, right) in a 14.6 ha Concord vineyard in Westfield, New York. The widespread overcropping (Ravaz Index > 10) of these vines in this year was due to a dry and warm season restricting vine size.

338x190mm (96 x 96 DPI)